Draft CEC PIER-EA Discussion Paper

Sea Level and Coastal Change

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Disclaimer

The purpose of this paper is to inform discussions among CEC staff, other state agency staff, non-governmental representatives, representatives of academia and other stakeholders regarding the state of research on physical coastal processes in California, especially with respect to sea level, waves, and coastal change monitoring. This paper focuses on what needs to be learned and monitored to enable prediction of future sandy-beach, seacliff, and wetland-estuary coastal changes in California in response to continued or accelerated mean sea level rise (MSLR). This discussion paper identifies gaps in our understanding and recommends future research and monitoring initiatives with the end goal of supporting informed and systematic planning for climate change-related MSLR. Note that this discussion paper is not a research proposal. However, it does of necessity refer to specific research programs, and makes some general recommendations regarding them.

1.0 Description of Research Topic

Rising sea level resulting from climate change allows more wave energy to reach farther shoreward, increasing the potential for greater coastal impacts. Mean sea level is the base level on which shorter duration fluctuations (such as El Niño-related increases, tides, storm surge, and waves) are superimposed. Coincident occurrence of extremes in these short-term fluctuations results in the greatest coastal impacts. Rising sea level augments extreme sea-level fluctuations, causing increased coastal erosion potential from wave activity.

The coastal erosion potential at a given location is a function of wave activity, exposure (local coastline configuration and bathymetry), beach slope (which may vary considerably between winter and summer), and geology (substrate and back-berm/seacliff composition).

Sea level rise impacts the coast in two basic modes: the first is simple inundation over immobile surfaces, formations, or structures (substrates); the second, and much more complex, is a combination of inundation and elevation and lateral position adjustments of movable substrates, such as a sandy beach. These impacts are discussed in more detail in the following sections.

Examples of immovable substrates include hard surfaces, such as: nearshore basal bedrock platform and other natural hard-rock features; roads and other paved areas (e.g., parking lots); and any fixed structures such as piers, revetments, seawalls, groins and breakwaters. Movable substrates in this context include erodible sandy beaches, seacliffs, and the sedimentary bottoms and lateral boundaries of coastal wetlands and estuaries.

A simplistic approach is to treat all coastal topography as immobile and unchanging. Possible future inundation can then be illustrated by simply drawing future sea level scenario elevations as contours on the assumed-static existing topography. This may be a very poor assumption in many cases, because seacliffs and beaches are already actively responding to storms. The effects of raised sea level on movable substrates—such as beaches, dunes, seacliffs, and wetlands—are very complicated, because these surfaces can erode, accrete, and/or move in response to both natural and human driving forces. Many of the forces that drive coastal change, including sea level, are themselves responding to climate change, and will have different characteristics in the future.

Anthropogenic factors can have significant coastal impacts. For example, seawalls can reduce cliff erosion but possibly accelerate beach drowning. Flood control and water storage projects can reduce river sand supply to beaches, but beach nourishment projects that place offshore sand on ocean shorelines can widen beaches. Sea level, or sea level rise, does not directly cause beach erosion or changes in the driving forces that affect shorelines. On most temperate-climate coastlines, including that of California, coastal erosion and inundation are driven by storm-forced extremes with coincident high storm surge, high ocean waves, peak high tides, and heavy rain. However, continued or accelerated sea level rise will undoubtedly increase the impact of storms and the need for shoreline protection structures.

The primary considerations of this paper are:

- How will sea level change as the global climate changes?
- How will California storm wave characteristics change?
- How will shorelines react to these (as yet unknown) changes in ocean conditions?
- How will engineering projects—ranging from dam removal, to new inland water storage, to seawalls—impact shorelines?
- How reliable are model projections?
- What additional physical processes can be monitored to most improve the reliability of estimates of ongoing and future coastal change?

A summary of existing knowledge in the areas of coastal sea level, waves, beach and cliff erosion, and wetland loss, as well as a summary of data and understanding gaps is presented in the following sections. A summary list of recommendations concludes the paper.

2.0 Summary of PIER Program Research to Date on Coastal Processes, Analysis, and Modeling

PIER has funded a very limited set of studies related to coastal processes, analysis, and modeling, which have producing the following reports:

- Market Impacts of Sea Level Rise on California Coasts (in *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy*) (Neumann et al., 2003).
- Projecting Future Sea Level (Cayan et al., 2006).

- More Than Information: What California's Coastal Managers Need to Plan for Climate Change (Moser and Tribbia, 2007a).
- Vulnerability to Coastal Impacts of Climate Change: Coastal Managers' Attitudes, Knowledge, Perceptions, and Actions (Moser and Tribbia, 2007b).

All of these PIER reports have resulted in papers published in peer-reviewed journals.

3.0 PIER Accomplishments

While all of the PIER supported studies should be considered exploratory studies, they have already made an impact. For example, the California Legislature specifically mentioned the research by Moset and Tribbia and the sea level rise projections generated by Cayan et al. (2006) in a bill that passed both the Senate and the Assembly, but was vetoed by the Governor. This bill would have required that all of the coastal management agencies consider sea level rise in their long-term planning processes using periodically updated sea level projections generated by PIER-supported researchers.

4.0 Non-PIER Accomplishments in this Area and Opportunities for Collaboration

Federal agencies, including the National Oceanic and Atmospheric Administration (NOAA), the Office of Naval Research (ONR), the U.S. Army Corps of Engineers (USACE), the U.S. Geological Survey (USGS), the National Science Foundation (NSF), among others, conduct and fund (or have funded) a substantial amount of coastal research. However, there is relatively little sponsorship of climate change-related research aimed specifically at California, or the other west coast states. The U.S. Environmental Protection Agency (EPA) and NOAA have funded studies of potential impacts of sea level rise on the United States as a whole, and more detailed studies are underway. But, these are mostly focused on the east and Gulf coasts given that those states are more vulnerable to sea level rise.

State and local agencies also support and conduct research, but thus far most of these studies have not been specifically designed to address the impacts of climate change. Exceptions include long-term studies and monitoring programs supported by the California Department of Boating and Waterways (DBW) and recent work funded by the Ocean Protection Council (OPC).

DBW has been sponsoring coastal monitoring and study projects, mostly at the Scripps Institution of Oceanography (SIO), since about 1976 under its Boating Facilities Oceanography Program. As part of this program, the full-time DBW Staff Oceanographer position was created in 1974 with the incumbent (currently Dr. Reinhard Flick) permanently stationed at SIO. Expenditures for these projects are now approximately $4 million per year, with over $1 million in state funds and the remainder from a combination of federal and other sources. An important goal of the program includes supporting graduate students and post-doctoral researchers. Relevant study projects currently underway include:

- *Coastal Data Information Program (CDIP)*: The nation’s premier coastal wave measurement, modeling, and prediction program is conducted by SIO. Supported by DBW, USACE, and other agencies, it is the longest-running and most important DBW oceanography project. Results are widely used and relied upon by the recreational and commercial boating communities, local boating and law enforcement officials, coastal recreational users, as well as scientists and engineers. The program is the basis for a coastal wave climatology that will be essential for progress in understanding and predicting the evolution of the California coastline.[1]

- *Southern California Beach Processes Study (SCBPS)*: Corps of Engineers supported projects to measure details of wave-driven beach change and shoreline retreat using regular twice-yearly Light Detection and Ranging (LIDAR) overflights. It is closely-related to CDIP and dependent upon its wave information, personnel, and the DBW-supported infrastructure.[2]
- *Cliff Erosion in the San Diego Region*—DBW-funded study at SIO that utilizes the SCBPS LIDAR surveys to determine cliff erosion and sand supply rates, and the causative mechanisms focusing, especially on waves and rainfall.
- *California Shore Station Program*—DBW supported long-term California coastal ocean monitoring program, which includes daily temperature and salinity measured at Scripps Pier since 1916. Continuation of these measurements and making archival data widely accessible is directly beneficial to climate change research in California.[3]
- *Sacramento-San Joaquin Delta Studies*—DBW program to document shore protection of delta levees, and the proportion of their erosion attributable to various causes.
- *Seismic Reconstruction of Wave Climate*—DBW-funded SIO study to use seismic measurements to reconstruct ocean wave data from the 1930s to the 1980s, before actual coastal wave measurements became available.
- *Tides and Sea Level*—Twenty-five-year DBW support for study of the long, medium, and short-term fluctuations in tides and coastal sea levels. Recently provided input to Governor's Climate Action Team report, among other publications. [4]
- *Coastal Waves*—DBW-funded collaborative work with Drs. Bromirski, Cayan, and Graham on the fluctuation of ocean wave conditions off the California coast,[5] among others.
- *Crescent City Tsunami Oscillations*—DBW-supported detailed study of the harbor oscillations from the 1960 Chilean earthquake undertaken as a SIO Masters Degree project.[6]

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[1] See http://cdip.ucsd.edu for more information.
[2] See http://cdip.ucsd.edu/scbps/ for more information.
[3] See http://shorestation.ucsd.edu for more information.
[4] See http://www.agu.org/pubs/abs/jc/1999JC900156/tmp.html and http://ams.allenpress.com/perlserv/?request=get-abstract&doi=10.1175%2F1520-0442(2003)016%3C0982%3ASVATCC%3E2.0.CO%3B2.
[5] See http://hebb.mit.edu/people/jfmurray/publications/Flick2003.pdf and http://www.agu.org/pubs/crossref/2005/2004JC002398.shtml.

- *Coastal Ocean Temperature*--Determining the biases associated with once-daily long-term pier temperature data, and what this may mean for "global warming" measurement.
- *Internal Tide Surges and Tide Range Increase*—Collaborative work to determine mechanisms for coastal secular changes in tide range.[7]
- *Tsunami Run-up Statistics*—Utilization of NOAA tsunami run-up database to determine run-up statistics in Hawaii.[8]

The OPC has made a commitment to climate change science with an initial investment of about $2 million that would be replenished periodically. As part of this overall effort, it is funding a project designed to develop hourly sea level rise scenarios for three sites in California. Cayan et al. (in preparation) are using methodology for estimating hourly sea level projections in the open ocean near San Francisco, developed for the PIER project on Projecting Future Sea Level (listed above) in combination with Rahmstorf's (2007) formalism to make improved sea level rise projections.

PIER maintains strong links with federal, state, and local agencies to avoid unnecessary duplication of efforts. In fact, given the limited PIER funds devoted to coastal studies, PIER resources are mostly used to build upon long-term efforts supported by others.

5.0 Research Underway/Committed to via PIER Process

The following relevant research projects are underway:

- Development of a coastal evolution model for California (P. Adams, University of Florida; and D.L. Inman, Scripps);
- Inundation Vulnerability Due to Sea level Rise in San Francisco Bay (N. Knowles, USGS);
- Assessing the Costs of Sea-Level Rise Along the California Coast and In San Francisco Bay (P. Gleick *et al*., Pacific Institute); and
- Estimating the Potential Economic Impacts of Climate Change on Southern California Beaches (P. Pendleton *et al*., Ocean Foundation and UC Los Angeles).

6.0 Gaps in Research/Knowledge Relevant to California

6.1 Mean Sea Level

For purposes of this discussion paper, "mean sea level" (MSL) is defined as any of various-length temporal averages of the sea surface elevation ranging from 1- or 6-minutes to 1-year. Most commonly, sea level is presented as hourly, daily, monthly, or annual averages measured by tide gauges. Tide gauge measurements are meant to exclude a host of rapidly varying wave fluctuations, including the common wind-generated gravity waves, but to include a suite of processes that affect sea level—including wind and barometric pressure-driven "storm surges," the tide, seasonal and

[6] See http://content.asce.org/files/other/SCD08FINALPROGRAM.
[7] See http://hebb.mit.edu/people/jfmurray/publications/Flick2003.pdf.
[8] See http://explorations.ucsd.edu/Around_the_Pier/2007/Oct/STARS/.

inter-annual climate forcing (e.g., El Niño effects), and the steric and eustatic contributions to long-term mean sea level and its changes.

MSL rise (MSLR) is herein defined as the long-term increase of mean sea level over time periods of a decade or longer. In a few California locations, including Crescent City, MSL is actually falling due to tectonic processes. MSLR is of concern because this rise inexorably exacerbates all kinds of short-term processes that flood, damage, and erode the coast and coastal developments.

Relative sea level (RSL) is a term often used interchangeably with MSL at any particular location. The distinction is important when comparing different kinds of sea level measurements at different ocean basins across the globe, such as those from tide gauges and satellites. Along the California coast for the past 100 years, MSL and RSL have been about the same.

Knowledge of California (coastal) sea level variability derives mainly and historically from the system of about a dozen NOAA long-term tide gauges that are distributed along the state's coast. These have various-length time histories, with the longest continuous record being from San Francisco, commencing in 1855 (Bromirski *et al*., 2003). Routine global sea level observations are available from satellites since about 1992.[9] Global coverage by the satellite data is a big advantage, especially for monitoring global mean sea level changes. However, for study of shorter-term sea level fluctuations, and for monitoring relative sea level at specific coastal locations or regions, tide gauge data are still the most useful.[10] This is partly due to the difficulty in making accurate satellite measurements at the ocean/coast boundary and satellite track coverage. The San Francisco tide gauge record shows that MSL rose about 22 centimeters (cm) over the 20th century (Flick et al., 2003), a value close to the best estimates of global MSLR over the same period (Church and White, 2006).

6.2 Past Mean Sea-Level Rise

While estimates of actual MSLR over the past century are fairly robust, estimates of the contributions of the various processes responsible certainly are not (Munk, 2002). The most important processes are: (1) the added water (eustatic) contributions of ice melt from land-bound glaciers and high-latitude ice caps[11] (i.e., Greenland and Antarctica); (2) the thermal expansion (steric) increase due to warming of ocean water; (3) groundwater pumping (which raises MSL); and (4) land-based water storage (which lowers MSL).

Table 6.1 is a summary of estimated contributions to MSLR over the 20th century, and over the decade from 1994–2004 (Nerem, 2008). Column 2 shows the observed MSLR (in cm per century, cm/cy), while the "total contributions" (Column 3) is the sum of Columns 4 through 8. Note that for both time periods, the sum of the best estimates of

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[9] See, for example: http://podaac.jpl.nasa.gov/.

[10] Tide gauges measure sea level relative to the land they are fixed to, while satellites measure sea level relative to the geoid. These may differ due to local uplift or subsidence. For purposes of coastal studies, tide gauges provide more readily applicable information, and the data is in a form that is much more easily processed.

[11] For the purpose of this paper, "ice caps" excludes the north polar ice cap since it is floating and therefore its melting does not raise MSL.

the contributions (Column 3) is lower than the observed MSLR by between about 10% and 60%. In other words, the observed MSLR over the past century or the past decade is less than the estimates of the sum of its contributing parts. Progress toward resolving this discrepancy has recently been made.

Table 6.1: 20th century mean sea-level rise and its estimated components

(1) (cm/cy)	(2) Total Observed	(3) Total Contributions	(4) Warming (Steric)	Melting Ice (Eustatic)			(8) Water Storage
				(5) Antarctic	(6) Greenland	(7) Glaciers	
1900–2000	18	8–14	7	1	1	5	-6–0
1994–2004	32	25–29	12	3	5	9	-4–0

6.3 Projected Mean Sea-level rise

Over the past several decades, tide-gage observations along the California coast indicate that sea level has risen at a rate of about 20 cm per century. In the future, as climate warms, it is nearly certain that the rate of MSLR will increase due to enhanced ocean thermal expansion and much increased melting of ground-based ice—primarily in Greenland and Antarctica. Table 6.2 summarizes the best estimates of these contributions for a total 100 cm MSLR scenario by 2100 (Nerem, 2008).

Table 6.2: 21st century mean sea-level rise and budget scenario.

(1) (cm/cy)	(2) Total Contributions	(3) Warming (Steric)	Melting Ice (Eustatic)			(7) Water Storage
			(4) Antarctic	(5) Greenland	(6) Glaciers	
2000–2100	100	20	25	30	25	unknown

Rahmstorf (2007) demonstrated that, over the last century, observed global MSLR is correlated with global mean surface air temperature. This semi-empirical method links MSLR to the observed increase in global mean temperature. This enables estimation of global MSLR from surface air temperature increases projected by general circulation model (GCM) simulations.

There is no expectation that any GCM model run will realistically predict conditions on any given day in the future. Instead, GCMs should produce the statistical characteristics of the climate over many years. However, the basic physics that explains how atmospheric temperature will increase in the troposphere as a function of greenhouse gas (GHG) levels is well established. Different GCMs having different parameterizations and implementations of the physics give globally-averaged warming estimates that are in reasonably close agreement. Consequently, of all the parameters that can be extracted from GCM projections, globally-averaged atmospheric temperature changes are generally considered the most reliable. Therefore, MSLR projections using the Rahmstorf methodology likely produce improved estimates for given GCM GHG emission scenarios, providing that the historical relationship between globally-averaged atmospheric temperature and MSLR persists.

Cayan et al. (in preparation) used the National Center for Atmospheric Research (NCAR) Community Climate System Model Version 3 (CCSM3) climate model "A2 (High) GHG" emissions scenario temperature simulations as input to the Rahmstorf model. It is assumed that MSLR along the California Coast will be the same as the global estimates. The Rahmstorf MSLR estimates were adjusted upward to account for the global increase of dam and reservoir storage during the 20th century, which has reduced surface runoff into the oceans and reduced MSLR. If future water storage in dams does not similarly expand going forward, MSLR will increase. Also, if ground water systems are increasingly exploited without offsetting the water volume extracted with an increase in storage capacity, MSLR will increase.

This combined model gives larger projected rates of MSLR than other recent estimates (e.g., Cayan et al., 2008). The resulting projections indicate that the potential sea level rise over the next five decades will increase over its historical rate by a considerable amount, accelerating towards the end of the 21st century to more than four times the current rate. Large, relatively rapid, increases in the rate of MSLR are important because they will likely cause large changes in shorelines, beaches, and coastal, tidal, and wetland ecosystems, as well as prevent/reduce their ability to reach equilibrium configurations typical of periods of RSL still-stand.

6.4 Sea Level Fluctuations

For practical purposes, there are only a few actions needed to improve the data from the tide gauge network. First, continuous Global Positioning System (GPS) monitoring should be extended to all tide gauges, so that water level changes can be differentiated from tectonic uplift or subsidence. This would link the tidal elevation reference datums along the coast, and make it easier to compare tide gauge and satellite sea level data. This would best be accomplished through an existing GPS project such as the California Real Time Network.[12]

Second, improvements in resolution and distribution of the tide gauge data should be made by NOAA. Products routinely available on the Internet include monthly average statistics of numerous tidal datums (Flick et al., 2003), and hourly and six-minute resolution data from all available tide gauges. One-minute resolution data is available by special arrangement with NOAA, but the process is slow and not automated. A number of interesting coastal wave processes could be examined with this higher-resolution data, including harbor seich[13] and other infragravity[14] wave propagation physics.

By far the greatest concern about tide gauge data availability is that federal budget pressures will lead to: elimination of some tide gauge stations; degradation in data quality control (which has been a problem in the past); delays in posting data on the Internet; and/or continued delays in making historical (mainly hourly) data readily available. Elimination of some, or even most tide stations, or the other concerns listed, would probably not affect monitoring or projection of long-term global mean sea level change. However, realization of any of these concerns would be detrimental to research programs aimed at the better understanding of coastal changes in California driven by short-term processes.

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[12] For more information, see http://sopac.ucsd.edu/projects/realtime/.

[13] Seich are the natural oscillations of an enclosed or semi-enclosed body of water, such as a lake or harbor.

[14] Infragravity waves refer to ocean surface oscillations in the period band ranging from 20-600 seconds—longer than the usual ocean surface gravity wind-generated waves.

Coastal change and flooding are caused by short-term processes, including storm-waves, and the co-occurrence of peak tides, storm surges, and El Niño-related inter-annual sea level increases. They are not driven *per se* by long-term MSLR. However, because these fluctuations are superimposed on MSL, MSL will be increasingly important if the MSLR acceleration projected at the end of the 21st century occurs. Without at least regional resolution (meaning 100-kilometer [km] spacing or less) and continuous, timely availability of sea level data, the continued analysis needed to better understand these processes would be hindered.

This is to say nothing of the value of the currently available NOAA tide[15] forecasts together with real-time information about the short-term departure of sea level from the tide. This information now enables coastal residents, public and private property managers, and local, state, and federal responders—such as sheriffs, police, lifeguards, and river-rescue teams—to routinely assess coastal flooding and damage potentials by simply examining this data on the Internet.

6.5 El Niño Considerations

During great El Niños, such as the 1982-83 and 1997-98 events, sea level along the California coast is elevated by 15–20 cm for a year or two at a time, resulting from a combination of high amplitude pole-ward propagating coastally-trapped waves and warm water off the coast. Consequently, over the course of several months, the rise in California coastal sea levels is comparable to that observed during the entire 20th century. Prior to the 1982-83 event, the 1940-41 El Niño stands out, suggesting that intense El Niños may be occurring more frequently. If that is the case, then we can expect a strong event within the next 10 years or so. The next extreme El Niños will afford the opportunity to closely monitor changes in impacts and the variability of key physical parameters under an equivalent relatively large increase in MSL. It is important to identify which coastal parameters are crucial, and begin baseline monitoring so that the magnitude of future changes under higher MSL can be estimated.

6.6 Coastal Flooding of Hard Substrates

Determining the effect of any given sea level rise scenario on a fixed, hard surface is relatively simple; it simply requires reasonably accurate topography/bathymetry data to make maps on which the current and future sea level elevations of choice can be displayed. These kinds of maps are familiar, especially those prepared by FEMA[16] that show inland and coastal flooding potential, or the more extreme inundation that can be expected from a tsunami.[17] A virtual cottage industry is arising to produce colorful maps of various California coastal segments depicted at various scales and painted with brightly colored elevation contour bands denoting what real estate various sea level

[15] The astronomical tide is the only oceanographic variable accurately predictable.

[16] FEMA flood maps may be found at: http://msc.fema.gov/webapp/wcs/stores/servlet/CategoryDisplay?catalogId=10001&storeId=10001&categoryId=12001&langId=-1&userType=G&type=1

[17] For example, see Wong, *et al*. (2005), available at http://gis.esri.com/library/userconf/proc05/papers/pap2000.pdf

heights would inundate.[18] For purposes of this paper, we assume that the underlying topographical data and GIS-based mapping techniques required for these efforts are all sufficient for the task.

We do note however, that for areas with relatively low beach slopes, small errors in the vertical elevation data can lead to magnified errors in the maps of what is or is not flooded at any given static sea level elevation. Therefore, when making such maps, it is important to include some estimate of these errors. It should also be noted that beach slopes are likewise subject to considerable inter-annual (seasonal) and decadal variability.

More importantly, these kinds of mapping projects consider flooding from only "static" sea level elevations. Away from the immediate shoreline (e.g., on city streets in low-lying coastal areas, a block or more from the ocean), the static versions of these inundation maps have and can continue to serve as guidelines for simple but useful planning, emergency management, utility agency, and first-responder tools. More sophisticated versions of such maps could be developed that take into account the hydraulic flow characteristics of flood waters around buildings and along streets, where dynamic considerations may be important.

However, damages in the California coastal zone usually occur because of a combination of episodic high water levels in combination with wave surges and wind-driven spray. The magnitudes of instantaneous storm-forced overtopping-water heights, velocities, and volumes over sea walls, roads, parking lots, and other hard coastal structures right at the ocean's edge are much more dependent on wave characteristics—especially wave heights—than they are on the sea level elevation. Likewise, coastal structural damage from this type of flooding is primarily due to the dynamic pressures from wave attack, and not from the water level *per se* (Armstrong and Flick, 1989). Wind-driven ocean water spray can also produce flooding and damage during very strong storm events.

We recommend that efforts be made to determine the shoreline areas most vulnerable to these kinds of episodic wave-driven inundation and damage. This should begin by applying results that are already available from wave observation and modeling efforts, discussed in subsequent sections of this paper. The main element missing, however, is a systematic, state-wide program to observe and mark maximum overtopping[19] and runup[20] heights and locations on the hard-surfaces near the ocean's edge during large wave-storm events.

These and related observations should begin immediately so that a quantitative predictive relationship between given offshore wave conditions and resulting runup and overtopping levels can be developed. This predictive ability is needed for the many vulnerable low-lying areas. Without such empirical relationships based on direct

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[18] For example, see San Diego Foundation (2008).

[19] Overtopping refers to the height of water or the rate of water flow over a beach berm or a coastal structure. The berm is the flat area at the back of the beach, and is generally its highest elevation.

[20] Runup is the flow of water up a beach or coastal structure, or the maximum extent of this flow. Both overtopping and runup are usually wave-driven.

observation, projections based only on modeling of future runup or overtopping will barely rank as "educated guesses," and certainly should not be used as a basis for potentially far-reaching and perhaps long-enduring policy decisions and choices.

6.7 Waves

Ocean surface gravity waves are generated by wind blowing over water and are characterized by their height, period, and direction of propagation. These wave parameters are summarized as a wave "frequency-directional spectrum," which is the distribution of wave energy (proportional to height squared) as a function of wave frequency (the inverse of period) and direction. The wave spectrum of deep-water ocean waves depends in turn on the strength of the generating wind field (wind speed), the size of the area the wind is blowing over (fetch), and how long the wind blows (duration). Big storms with strong winds that blow over large ocean areas for several days generate high waves with long periods (i.e., low frequencies).

Waves provide nearly all the energy that drives physical processes along the California coast, and the occurrence of high waves relative to tidal extremes is of critical importance. Both the generation of waves by wind over the ocean and their propagation across the continental shelf are enormously complicated processes.

Understanding the details of coastal wave processes is paramount in developing the ability to anticipate the location of future erosion hot-spots, and to address the more general problem of coastal evolution needed to predict quantitatively the possible future configuration of California's coast under different sea level rise scenarios. Wave conditions at the coast depend both on the wave conditions offshore and critically on their transformation as they travel over and around the complicated bathymetry off the California coast—especially in southern California.

Because of the importance of waves, the central technical issues that need to be addressed are:

(1) How best to characterize the waves at the coast?

(2) What needs to be done to better relate the changes in coastal wave conditions to changes in the coastal configuration?

In order to estimate the evolution of the California coast, we must first be able to relate past and currently observed coastal changes with past and currently observed wave conditions. Without such an understanding, predictions of future coastal change should not be relied on.

Wave measurement and modeling have advanced greatly over the past 30 years as instrument measurements have improved and expanded, and computer power has increased. Wave-generation physics describes how wind fields over the ocean generate ocean gravity waves. Wave models include both the generation and propagation of gravity waves forced by distributed wind fields. The reliability of modeled wave amplitudes depends on the accuracy of estimates of the temporal and spatial variability of the structure and strength of the winds. However, wind estimates necessarily are averages over some spatial scale that may have insufficient resolution to accurately characterize wind field gusts, causing extreme winds and local winds to be generally underestimated. Local wind fields (that are difficult to estimate) can make about a 1 meter (m) contribution to observed wave heights. Consequently, although model wave statistics match observations reasonably well, the maximum observed wave height is often under-predicted.

A current OPC-funded study, using Wave Watch III (WWIII) (Tolman, 2002) wave model swell estimates with forcing by NCAR GCM CCSM3a2 model winds (Bromirski et al., in preparation), shows a general decrease in the winter wave 98th percentile, likely associated with a northward shift in storm track. Comparison of modeled extremes with buoy observations over the same time period shows that model extremes generally underestimate observations. This is partly due to WWIII not including contributions from local winds, and also possibly because the peak wind speeds during the largest storm events are underestimated.

The dominant physics affecting shallow water waves along the California coast are refraction and shoaling, which are complicated by island and headland sheltering. Both the Simulating WAve Nearshore (SWAN) model (Holthuijsen et al., 1993) and the California Data Information Program (CDIP) coastal wave system (O'Reilly and Guza, 1991; 1993) include these factors. However, the CDIP model has been optimized for use on a state-wide basis with the CDIP wave buoy network, and utilizes a numerical algorithm that minimizes wave direction errors in very shallow water just prior to wave breaking. This shallow water directional wave information is critical to predicting the correct direction and magnitude of surf zone currents and sediment transport, as well as estimating wave runup-associated coastal erosion potential. In addition, the CDIP model is being extended to assimilate local winds so that the locally-generated short period component of the wave spectrum is included. Application of CDIP methodology to the CCSM3a2 wave model projections for estimating projected runup (Bromirski et al., in preparation) and shoreline changes as part of OPC-funded research is currently underway.

6.8 Coastal Change

Coastal change in California is generally dominated by coastal retreat, be it the beaches or the seacliffs. The underlying reason for this is that the California coast is geologically young, and thus reflects its recent (5–20 million-year old) tectonic history (Inman and Nordstrom, 1971). The continental shelf is relatively steep and narrow compared with the east and Gulf coasts of the United States. Because of its basic geological setting, the California coast is by nature an eroding coast being acted upon by wave forces abetted by rising sea level.

The California shore zone is generally characterized by a gently sloping basal bedrock platform covered with a thin veneer of sand forming a beach. The nearshore zone is backed by either dunes a few meters high or steep seacliffs of varying height from a few meters to several hundred meters. The cliffs represent the seaward edge of the uplifted coastal marine terraces formed by wave action during previous still-stands of sea level. River valleys and other erosion or tectonically-controlled features often bisect these terraces. The drowned valleys form coastal wetlands and estuaries (for example, see Elwany et al., 1998; 2003).

Coastal change research in California and elsewhere generally combines observations with process-based models. That is, models are calibrated and tested with observations, rather than derived from "first principles." There are simply too many unknowns and complicated processes, ranging from the details of the cliff geology and beach sand grain sizes, to the turbulent hydrodynamics of wave breaking, for purely theoretical approaches to work.

6.9 Coastal Change Measurement

The most common, earliest, and longest-term coastal change measurements involve analysis of vertical aerial photos and maps. Hapke et al. (2006) and Hapke and Reid (2007) show detailed results of this approach for the long-term beach and cliff erosion rates for the state. Professor Gary Griggs and his students (including Hapke) at the University of California-Santa Cruz have worked for many years to obtain, rectify, and analyze aerial photos for this task.

Air photos are most useful for following seacliff retreat because the cliff edge is often relatively easy to accurately delineate on air photos. The "wrack line," or approximate position of the maximum runup during the preceding high tide, can also be determined from air photos. However, without applying corrections for sea level height and properly accounting for the (usually unknown) effects of the wave conditions on the runup during the time the wrack[21] was deposited, this alone is insufficient to accurately determine the actual height of the runup. Therefore, comparison of successive wrack line positions on air photos is not an accurate way to determine beach width change, let alone to surmise beach profile changes.

Another popular method of tracking beach width and sand volume changes over time is by measuring beach profiles. This involves standard surveying techniques to measure the height of the beach as a function of distance from a fixed back-beach position (benchmark) along cross-beach transects as perpendicular to the shoreline as possible. Successive beach profiles at each transect can then be compared over time to quantify the elevation, width, and sand volume changes. The most useful profiles extend beyond the water line into depths of at least 5 to 10 m. However, this requires standard land surveys on the beach face and spatially overlapping, concurrent fathometer surveys farther offshore. The presence of waves and currents makes this survey method difficult and labor intensive, although the availability of laser "total station" and GPS survey gear over the past 20 years has made the chore somewhat less difficult.

Older "rod and level" surveys had horizontal and vertical errors of about 10 cm on the dry beach, but much larger errors in the underwater surveys that could reach many meters in the horizontal and 30 cm in the vertical.

The availability of inexpensive and accurate GPS has simplified both the land and water portions of beach profiling and area surveying. GPS has made it possible to survey relatively large beach and offshore areas much more quickly, accurately, and less laboriously, which means more affordably. Many research universities and government labs rely on this method, including Scripps Institution of Oceanography and the USGS, who pioneered the technology. Nevertheless, even this technique has its limitations,

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[21] Wrack refers to the debris that is pushed up the beach face by runup. It is usually composed of kelp, other floating natural debris such as logs, or trash. The wrack line marks the highest position of the runup during the previous peak high tide, and is often visible on air photos.

namely the area that can be covered in a given amount of time. Survey programs can be practically carried out at daily to weekly intervals over coastal lengths up to about 10 km. GPS surveys data have errors in the 10 cm range, both horizontally and vertically.

Overall, many thousands of beach profile and aerial surveys have been taken since the method was first widely used in California in the 1930s. The USACE and the Los Angeles County Department of Beaches and Harbors made the first surveys using an elaborate system of baselines and fixed profile ranges in the Los Angeles area.

Conventional beach survey data is still gathered regularly in the San Diego region by the San Diego Association of Governments (SANDAG). Other cities, counties, and organizations also collect beach profile and survey monitoring data, either regularly or as part of project monitoring requirements. These efforts should be continued, coordinated to the extent possible, and the data collected and archived at a central location.

The latest (and truly "greatest") technology to measure coastal change has applied LIDAR[22] technology, initially developed for surveying the Greenland ice sheet. This usually involves flying an airplane with a LIDAR system and precise GPS-based navigation. The light is swept across the topography as the plane is flown over the beach (Young and Ashford, 2006; Young et al., 2008). Truck-mounted horizontal-pointing LIDAR systems have also been used to measure cliff change. By using post-processed GPS information recorded simultaneously, vertical and horizontal accuracy in the 5–10 cm range can be achieved for ground patch sizes on the order of 50 × 50 cm over track lengths of hundreds of kilometers.

The main disadvantages of air-borne LIDAR surveys are their expense and the fact that current LIDAR sensors often cannot penetrate the water reliably, therefore limiting surveys to the dry beach. Equipment, flight time, and processing and interpretation costs for a typical southern California over flight reach $100,000. Nevertheless, the data accuracy, density, and extent represent a breakthrough in coastal change measurement capability.

This is especially so for seacliff measurements, which can be made in no other way. Several LIDAR programs exist in California. These include a routine, regional effort in southern California by Scripps Institution of Oceanography, and opportunity-based intermittent over flights by the USGS. These programs should be expanded state-wide and in frequency, and coordinated. A state-supported center, preferably at a University of California campus, is needed to run a dedicated LIDAR sensor, airplane, and analysis center. This is the best way to gain the benefits of this amazing technology.

6.10 Coastal Change Modeling

The coastal engineering community must devise estimates of coastal changes on a case-by-case project basis, often with tight time and budget constraints, and with limited information about past shoreline behavior or driving forces (e.g., waves) at the project location. Un-validated coastal change models, or models developed for other locations

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[22] LIght Detection and Ranging is similar to RADAR, but instead of using radio frequency waves, it uses light signals to measure the azimuth and distance to an object from a known instrument location.

with different settings or forcing, are sometimes used out of necessity. However, surf zone waves and currents, when modeled using the measured beach bathymetry and incoming wave characteristics, agree well with observations (Yates et al., 2008).

The first process-based models involved the physics of wave-driven sand transport (Bagnold, 1946; 1966; Inman and Bagnold, 1963), both alongshore (Komar and Inman, 1970) and on-offshore. USACE has compiled the most complete manual of coastal engineering formulas and models in the various generations of its "Coastal Engineering Manual" (previously called the "Shore Protection Manual," whose name well characterizes its main use). Hundreds of refinements have been published over the past 50 years. Over the past decades, dozens of wide ranging computer-modeling applications have been available, lately with relatively user-friendly front ends. These include commercialized USACE products, but the most sophisticated of these are sold by various European research laboratories, including the Delft Hydraulics Lab, among others.

Some aspects of wave-driven beach change, for example the on- and off-shore migration of a large surf zone sandbar at Duck, NC, have been simulated with some fidelity using observed waves and currents to drive a sediment transport model. However, shoreline change models in general suffer from very limited field validation.

USACE modeling programs include "Storm-induced BEAch CHange model (SBEACH)," which was developed to model beach erosion response to storm waves. It is widely used for this purpose by the engineering community. It is also widely misused to model beach accretion and normal beach erosion-accretion cycles, purposes for which it was not intended. While the USACE has made efforts to monitor project performance, little if any scientific (peer-reviewed) literature exists that rigorously tests the predictions of SBEACH, or its shoreline plan-form change model counterpart, "GENEralized model for SImulating Shoreline change (GENESIS)."

In shallow water, the alongshore transport rate is only a function of depth, wave height, and breaker angle, and can in principal be calculated if the wave field and beach configuration are known or assumed. From this, transport rate divergence (or convergence) can be calculated, and rates of erosion or accretion at each point estimated. The groundbreaking work of Komar and Inman (1970) describes the rate of wave-driven sand transport. Using their formalism in a differential mode, Adams and Inman (2008) calculate the divergence of the alongshore drift by modeling the amount of sand entering a "control volume" from up-coast and subtracts the amount leaving down-coast. If the difference is positive, the rate of sand entering is larger than that leaving, and the beach at that location must be accreting. If the difference is negative, the opposite is true.

One major limitation, however, is that without simultaneously modeling the on-offshore transport rates in the shoreline control volumes, a potentially important component of the sediment budget at each point along the shoreline is unaccounted for. This can lead to large errors in the erosion-accretion estimates. This is roughly equivalent to keeping track of the momentum budget, while ignoring the energy budget.

A second major problem is that the wave characteristics have until recently never been known precisely enough to calculate the divergence rates accurately under real coast conditions. This often causes the direction of predicted sand transport to be incorrect, with the magnitude even less certain. This problem can either be due to the presence of complex wave conditions, with wave trains from different directions competing, or because when the waves are very close to normally incident, small errors in the chosen local coastal orientation lead to sign errors in the transport direction. These problems are magnified where there are headlands, or any other kind of complicated nearshore or offshore topography.

A final weakness is that no known long-term comparisons of detailed shoreline change model predictions with actual measured waves and shoreline changes have been published, at least for California. The newly acquired ability to gather coastal beach and cliff change data with LIDAR, outlined above, and the development of a comprehensive wave measurement, modeling, and prediction system by CDIP may improve this situation over the next decade (Yates, et al., 2008; Young, et al., 2008).

The main conclusion is that at the present time, process-based coastal change models have not been proven to work. For this reason, it is risky to base policy decisions on the output of such models. Furthermore, modeling efforts should be much more closely joined with the data gathering efforts outlined in the previous section. Funding these efforts separately and independently is wasteful and counter-productive.

7.0 Conclusions and Recommendations

7.1 Conclusions

MSLR is likely to accelerate towards the end of the 21st century, while the wave climate along the California coast will likely be similar to recent activity. Rising sea level raises the base level on which the shorter-term sea level fluctuations and wave activity are superimposed, causing more wave energy to reach farther shoreward. Consequently, the potential for greater coastal impacts and increased coastal erosion from extreme storm events will rise. In the future, moderate storms will have impacts comparable to current extreme events.

California beaches and cliffs are already changing, and these changes are not well understood. For example, the interplay of rain and waves in southern California seacliff erosion is only now becoming apparent (Young et al., 2008). Sand levels on most California beaches have not been regularly monitored over time, and seasonal, storm, and long-term erosion rates are poorly known. Our understanding of beach processes is so limited that we have not even been able to accurately predict the longevity of recent beach nourishment projects, or the response of beaches to storms.

This limited fundamental understanding of present-day coastal change, together with the uncertainties in forecasts of future MSLR, climate, and sediment supply, clearly precludes accurate predictions of future coastal change. Continued and expanded monitoring of actual coastal change as it occurs in the future, the waves that drive this change, and the shoreline response to engineering projects (e.g., sea walls), can provide information that will prove vital to maintaining some sandy beaches in California in the future.

There are large gaps in the data needed to make reliable assessments and projections of both the extent and location of vulnerable portions of the California coast. A long-term, continuous monitoring effort to collect measurements of critical coastal physical parameters should be implemented. Without these needed data, projections will be unreliable, and plans made using these projections will ultimately result in costly avoidable losses.

7.2 Recommendations

It is risky to base policy decisions on the output of existing coastal change models that are not carefully calibrated with comprehensive coastal wave information, and ground-truthed with actual coastal change observations. With this in mind, and based on the research gaps noted above, the following activities are recommended:

- Implement a systematic, dedicated, state-wide program to observe and mark maximum overtopping, runup heights, and locations on the hard surfaces near the ocean's edge during large wave-storm events to determine locations most vulnerable to future sea level rise.
- Prepare simple coastal flooding maps at various scales for the entire California coast for a range of future sea level rise scenarios, and for a number of different tidal datums (e.g., MSL, mean high water [MHW]).
- Determine if and where hydraulic conditions of flood flow around buildings and along roads may be important in altering flooding potential, and incorporate these into the flood maps.
- Implement a systematic, dedicated, state-wide program to observe and mark maximum overtopping and runup heights, and locations on the sandy beaches during large wave-storm events to determine which beaches are most vulnerable to future sea level rise.
- Continue and expand upon studies of extreme coastal oceanographic and atmospheric conditions during previous large storm events and their probability of co-occurrence, with a focus on regional (100-km) scales.
- Determine how best to characterize the nearshore wave environment and develop state-wide, historical wave climatology on this basis that is easily available on the Internet. Scripps Institution of Oceanography's CDIP model is the ideal (and only available) platform for this purpose.
- Continue, expand, and coordinate the several existing LIDAR over-flight survey programs to systematically and regularly survey the entire California coast at monthly intervals, or at least four times per year.
- Institute a permanent and dedicated state-sponsored and maintained LIDAR sensor package, airplane, and analysis center at one of the University of California campuses to exploit the potential of this technology to monitor future coastal change.
- Closely join coastal change modeling efforts with data gathering efforts. Funding these efforts separately and independently is wasteful and counter-productive.

- Continue and coordinate the existing local conventional beach survey data gathering operations and collect the data in one central place.

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